

When Ecology Needs Economics and Economics Needs Ecology: Interdisciplinary Exchange in the Age of Humans

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ABSTRACT

Evidence that humans play a dominant role in most ecosystems forces scientists to confront systems that contain factors transgressing traditional disciplinary boundaries. However, it is an open question whether this state of affairs should encourage interdisciplinary exchange or integration. With two case studies, we show that exchange between ecologists and economists is preferable, for epistemological and policy-oriented reasons, to their acting independently. We call this “exchange gain.” Our case studies show that theoretical exchanges can be less disruptive to current theory than commonly thought—valuable exchange does not necessarily require disciplinary integration.

1. Introduction

The growing Anthropocene consensus, that humans are a major geological and environmental force on par with natural forces, has proven to be a hotbed for discussion beyond the science of geology (Steffen et al. 2007; Thomas 2014; Bonneuil and Fressoz 2015; Corlett 2015; Purdy 2015). One reason is that it forces scholars to confront problems and systems that contain factors transgressing traditional disciplinary boundaries. This is especially so for the sciences of ecology and economics: economics has by and large explicitly ignored the “natural” environment, while ecology has largely focused on it exclusively (O’Neill and Kahn 2000; Dasgupta 2010; Martin et al. 2012; Inkpen forthcoming-a). One consequence of the Anthropocene consensus is that the distinction between human and natural systems is no longer firm: human-natural coupled systems are not exceptions, they are quickly becoming the new norm (Pickett et al. 2005; Liu et al. 2007a, 2007b). Economics and ecology, deliberately separated in the nineteenth-century on the basis of different research objects and objectives, are now rethinking their separation, as evidenced by transdisciplinary research programs such as “ecological economics”.¹

There is a growing body of literature in philosophy of science examining interdisciplinarity. This literature traces back to Lindley Darden and Nancy Maull’s classic paper about “interfield theories,” but has recently accelerated at a quickening pace, perhaps as a result of the increasing interdisciplinary nature of contemporary science itself (Darden and Maull 1977; see the recent edited volumes by Brigandt 2013, Grüne-Yanoff and Morgan 2013, Grüne-Yanoff and Mäki 2014). This literature has focused on a broad range of issues, including: traditional philosophical problems, such as reductionism and incommensurability (Mitchell 2003, Longino 2013); the conceptual, methodological and theoretical entities that are exchanged between disciplines (Rice and Smart 2011); the types of exchanges that occur between disciplines (Grüne-Yanoff and Mäki 2014); whether interdisciplinary exchange has been productive or detrimental (Plutynski 2013; Love and Lugar 2013; Mäki 2013); and the reasons for interdisciplinary integration and exchange, whether ontological, methodological, or epistemological (Mitchell 2009; Brigandt 2013).

Despite growing in scope, this literature has so far ignored one of the primary drivers of interdisciplinary science today: the Anthropocene consensus (Bonneuil and Fressoz 2015).

¹ Ecological Economics is a policy-oriented school of thought that emerged as a formal institution in the late 1980s, with its origins extending back to Nicholas Georgescu-Roegen’s *The Entropy Law and Economic Processes* (1971) (Costanza 1989; Christensen 1989; Røpke 2005; Martinez-Alier and Røpke 2008).

What are the implications, if any, for interdisciplinary exchange between ecology and economics that arise from a world that contains a mixture of anthropogenic and non-anthropogenic factors?

We argue, first, that the collapse of the distinction between natural processes and societal processes inherent in the Anthropocene consensus has signaled the causal entanglement of the objects traditionally studied by ecologists and economists. We claim that this can be construed as the breakdown of a disciplinary idealization: that ecology is to ignore anthropogenic factors and economics, in general, is to ignore the non-anthropogenic factors. Focusing on two case studies—one demonstrating ecology’s need of economics, and the other showing economics’ need of ecology—we argue that excluding anthropogenic factors from ecological models and non-anthropogenic factors from economic models lessens their predictive success. This mutual dependence rests on the fact that the target systems for both disciplines include anthropogenic and non-anthropogenic factors and, as we will show, excluding one set of factors is not an innocuous idealization. Finally, we argue that disciplinary interactions should be scientifically informed, that is, based on evidence of greater predictive success or explanatory power, rather than on reasons of disciplinary identity or purity, as has been the case in the past.

This paper engages with the recent literature on interdisciplinarity in the philosophy of science in three ways. First, this literature has focused on enumerating the conditions underwriting the possibility and success of interdisciplinary exchange.² We ask the following question: what makes interdisciplinarity necessary or worth advancing? We argue that the recognition that so-called human-natural coupled systems are the new norm should encourage exchanges between ecology and economics: in the cases provided below, exchange between these disciplines is epistemologically preferable to their acting independently. We call this *exchange gain*. Second, as Grüne-Yanoff and Mäki (2014, 58) suggest, this literature would benefit from studies of how disciplines can undergo successful exchanges without requiring

² A note about terminology. In the interdisciplinarity literature, interdisciplinary exchange, transfer, collaboration, and integration have separate and specific meanings. An exchange occurs if objects, broadly construed, employed in one discipline are used to solve problems of another discipline. A transfer occurs when agents from only one discipline pursue an exchange. A collaboration occurs when agents from both disciplines jointly pursue an exchange. Disciplinary integration occurs when an exchange forces some significant breakdown of disciplinary boundaries. In the most extreme case, integration involves the complete breakdown of boundaries.

disciplinary integration. The two cases below demonstrate that theoretical exchanges can be less disruptive to current theory than might be expected—disciplinary exchange brings epistemological advantages without requiring disciplinary integration. Third, in accordance with this literature’s aim to provide a comprehensive taxonomy of interdisciplinary exchange types, we provide two new types: *non-disruptive model-variable transfer* and *non-disruptive model-system transfer*.

Our paper proceeds as follows. Section 2 explains the Anthropocene and its implications for interdisciplinary research. It also lays out our argument explicitly. Section 3 summarizes our contribution to the recent literature about interdisciplinarity. Sections 4 and 5 provide case studies of interdisciplinary exchanges between ecology and economics, respectively. Section 6 concludes.

2. Interdisciplinary Exchange in the Age of Humans

Imagine a world in which ecology and economics get on quite well without one another. This is a world that is made up of relatively independent human and natural systems: one set of systems, the object of ecology, consists of non-anthropogenic or “natural” factors; another set, the object of economics, consist of anthropogenic or human factors. In such a tidy world, these sciences, when operating effectively, make successful predictions and prescribe policy interventions without the need for interdisciplinary exchange.

Throughout much of the twentieth-century this imaginary world seems to have been implicitly assumed. As ecologist Robert O’Neill and economist James Kahn wrote in 2000:

the current paradigm in ecology considers humans not as a keystone species [a dominant species on which other species within an ecosystem depend] but as an external disturbance on the “natural” ecosystem. [...] The problem with this approach is that human beings are, in fact, another biotic species within the ecosystem and not an external influence.

But the artificial isolation of humans from their ecosystem is not due only to the ecologists’ paradigm. In the economic paradigm as well, human society, with all of its self-organization and self-regulatory activity, is represented as a separate “system.” The ecosystem is viewed as external to society, providing goods and services, unoccupied territory in which to expand, and assimilative capacity to handle by-products. [...] The

ecological paradigm isolates human activity in a box labeled “disturbances.” The economic paradigm, in turn, isolates ecosystem dynamics in a box labeled “externalities.” (O’Neill and Kahn 2000, 333)

Of course, this imaginary world is just that, a fiction. The real world is messy. Strictly speaking, there is no longer any part of the earth’s surface that remains completely detached from human technologies (McKibben 1990; Bensaude-Vincent and Newman 2007; Wapner 2010; Vogel 2015). By the late 1990s, it was estimated that up to one-half of the earth’s land surface was transformed by human action (Vitousek *et al.* 1997). Today, roughly 75% of ice-free land on earth has been transformed by agriculture and human settlement changing ecosystem patterns and processes across most of the terrestrial biosphere (Ellis and Ramankutty 2008; Martin *et al.* 2012; Ellis *et al.* 2013). Human presence is so pervasive on earth that some argue it marks a new geological epoch, the Anthropocene (Steffen *et al.* 2011).³ The world today is a blend of anthropogenic and non-anthropogenic factors and *prima facie* this seems like a world in which exchange between ecology and economics would be a prerequisite to successful science.

Recent discussions in the philosophy of science about idealization can help illuminate this state of affairs (Weisberg 2007).⁴ Invariably, theorizing involves intentional distortions and simplifications, and theoreticians must make decisions about which factors to include in their models and which to ignore. These decisions can be made for pragmatic reasons, for example, to simplify a model so that it is computationally or cognitively tractable (referred to as *Galilean Idealizations*). They are also made because ignoring some factors is believed to be causally innocuous (*Minimalist Idealization*). The relevant concerns for any idealization are (i) whether the factor that was omitted from, or distorted in, the model would substantially change the predictions or explanatory power of the model if it had been taken into account, and (ii) if the predictions or explanatory power are substantially changed, what we should do

³ The term “Anthropocene” was coined by Nobel laureate Paul Crutzen in year 2000 to describe the current geological epoch that is characterized by the enormous role that human activity has for geological and ecological phenomena (Jones 2011).

⁴ Following Jones (2005) it has been common to draw a distinction between *idealization* and *abstraction*, the former being the assertion of a falsehood, the latter being merely an omission. In this paper, I follow Weisberg’s (2007) pluralist account and treat abstraction as a form of minimalist idealization, as I explain below.

about the idealization. Practitioners making Galilean idealizations would justify the omission of such factors on grounds of tractability; those making minimalist idealizations could not justify such omissions.

We argue that there are cases in which ignoring economic factors leads to poor predictions in ecology and cases when ignoring ecological factors leads to poor policy prescriptions in economics. For all such cases, if we presume that *the goal is to obtain successful predictions and, ultimately, recommend successful policy interventions*, then both types of idealizations are unwarranted. In other words, if the best predictions and prescriptions for policy intervention require hybrid economic-ecological models containing anthropogenic and non-anthropogenic causal factors, then such factors should not be omitted merely on grounds of idealization.

The main argument of this paper can be summarized as follows. The world is now made of systems containing interdependent anthropogenic and non-anthropogenic factors, but ecology has tended to idealize anthropogenic factors and economics has tended to idealize non-anthropogenic factors. Although idealizations in general can be justified pragmatically or because they are innocuous, our claim is that not every idealization in ecology and economics can be so justified. We question whether the idealizations in ecology and economics are justified pragmatically given, first, that model exchange can in some cases be quite non-disruptive and thus *not* a computational or cognitive burden, and, second, that our best chance of providing successful predictions, and also successful policy interventions, is model exchange. Furthermore, we claim that, in the past, what justified these idealizations was often neither pragmatics nor innocuousness, but instead “disciplinary purity.” Reasons of disciplinary purity should never trump epistemic reasons, such as greater explanatory potential or predictive success and, thus, this reason is unwarranted as well. We conclude that the recent evidence, which suggests that many of the world's systems contain interdependent anthropogenic and non-anthropogenic factors, is a new and independent reason for promoting and fostering interdisciplinary exchange.

3. Interdisciplinarity and the Philosophy of Science

In recent years, philosophers of science have shown a growing interest in inter- and transdisciplinarity science (Gibbons *et al.* 1994; Brigandt 2013; Longino 2013; Love and Lugar 2013; Grüne-Yanoff and Mäki 2014; Macleod and Nagatsu 2016). Many acknowledge

that collaborations between researchers working in different disciplines is a requirement for addressing the complex environmental, societal and medical problems that we face, and so frameworks that help us to understand when and why such collaborations will be productive are essential. This literature has focused on a number of questions, including: What social, institutional, and organizational factors hinder interdisciplinary exchange? What factors promote exchange? How do different disciplines coordinate and modify their existing conceptual frameworks and methods? How do they come to terms with different epistemic and explanatory standards?

This paper contributes to this literature in a novel way by focusing on specific cases that makes interdisciplinary science imperative. We argue that recognizing that human-natural coupled systems are the new norm should encourage exchanges between ecology and economics, exchanges that have traditionally been discouraged by disciplinary boundaries. One standard worry is that interdisciplinary exchange requires an unrealistic or burdensome level of integration between two disciplines. However, the case studies we provide below demonstrate that this is not always the case. Significant epistemological advantages can be purchased, in some cases, relatively cheaply, without requiring disciplinary integration and with minimal collaboration.

The following case studies also speak to some of the more traditional questions about interdisciplinarity. For example, the specific epistemic virtues generated by interdisciplinary exchange between ecologists and economists. MacLeod and Nagatsu (2016) follow a similar line of reasoning when they argue that successful interdisciplinary collaboration provides practitioners with “collaborative gains,” such as better predictive power or explanatory scope. Because our case studies of interdisciplinary exchange involve little bidirectional collaboration compared to that of MacLeod and Nagatsu (2016), we will call these epistemological and policy-oriented advantages “exchange gain.”

Before providing the details of these case studies, we would like to fit the types of interdisciplinary exchange we present—*non-disruptive model-variable transfer* and *non-disruptive model-system transfer*—into the helpful taxonomy that was originally developed by Grüne-Yanoff and Mäki (2014, 55). These authors summarize the general characteristics of interdisciplinary exchange as follows: “Let there be two disciplines, A and B, with the respective (i) A-agents and B-agents, (ii) A-objects and B-objects, and (iii) A-problems and B-problems. Different combinations yield 13 distinct cases (allowing for an

outside object X in case 13)” (Grüne-Yanoff and Mäki 2014, 55). These cases, plus one of our own (14*), can be summarized in the following table (Table 1; modified from Grüne-Yanoff and Mäki 2014, 55):

Table 1: Possible interdisciplinary exchanges in a two-discipline environment

	who uses?	what objects?	what problem?
1. within-discipline	A	A	A
2. exportation	A	A	B
3. importation	A	B	A
4. move	A	B	B
5. move	B	A	A
6. importation	B	A	B
7. exportation	B	B	A
8. within-discipline	B	B	B
9. personal collaboration	A&B	A	A
10. transfer collaboration	A&B	A	B
11. genuine collaboration	A&B	A&B	A
12. new field generation	A&B	A&B	A&B
13. parallel development	A/B	X	A/B
14.* interfield importation	B	A&B	B

Our first case study (Section 4) provides an example of (3), what is called *interdisciplinary transfer by importation*: A-agents use B-objects to address an A-problem (where “A” is ecology and “B” is economics). But to get at the precise details of interdisciplinary exchange, and to make the point that some exchanges are less disruptive to current discipline-specific theory than others, we further characterize this example as (i) *non-disruptive* and (ii) *model-variable transfer* (i.e., the transfer involves simply substituting an economic variable for an ecological variable, rather than an entire model). Our second case study (Section 5) provides an example of (14), what we are calling *interfield importation*: B-agents use models that combine A&B-objects to address B-problems (again, “A” is ecology, “B” is economics). As in our first case study, we further characterize this example as (i) *non-disruptive* and (ii)

model-system transfer (i.e., the transfer involves connecting a traditional economic system to an ecological system with feedback links).

Finally, our analysis provides further evidence to support the claim that successful interdisciplinary interaction does not always require the integration of disciplines, a thesis that was recently defended by Grüne-Yanoff (2016). Taking the specific cases of evolutionary game theory and hyperbolic discounting, Grüne-Yanoff argues that integration, to be understood as the growing cohesion of concepts, practices, explanations, ontologies, methods and data among distinct disciplines, is not a necessary condition for successful interdisciplinary science. With the help of our case studies, we reach the same conclusion. In the case of interdisciplinary exchange between ecology and economics, considerable epistemic gains, along with improved policy prescriptions, can be obtained without a thoroughgoing integration of ecology and economics. While we do not deny that there may be some cases that would require the complete integration of ecology and economics, our claim is that such an assimilation is not a necessary condition for attaining the epistemological benefits that arise from interdisciplinary exchange between ecology and economics. The disciplinary identities of these two sciences can remain, on the whole, intact.

4. When Ecology Needs Economics: Island Biogeography in the Anthropocene

Traditionally, ecologists have ignored anthropogenic factors, often discounting human activity as external to ecosystems and treating humans as exogenous variables or disturbing conditions (O'Neill and Kahn 2000; Martin et al 2012; Worm and Paine 2016; Inkpen forthcoming-a, forthcoming-b). Ecologist James Brown writes that the “study of humans and their interrelationships with the rest of the natural world has been left to the ‘social’ and the ‘applied’ sciences, both of which have been viewed with disdain by many of those who practice ‘pure’ ecology” (Brown 1995, 205).⁵

As Collins *et al.* (2000) suggest, one reason for this treatment of anthropogenic factors is the assumption that human-disturbed environments are unpredictable from an ecological standpoint. Human actions are often governed by individual whim or social forces—whether

⁵ According to Laura Martin and colleagues, “most ecologists have assumed that (seemingly) unpeopled environments better represent ecological and evolutionary processes and are therefore better objects of study” (Martin *et al.* 2012, 198). And James Collins and colleagues write that “From the perspective of a field ecologist examining a natural ecosystem, people are an exogenous, perturbing force” (Collins *et al.* 2000, 416; see also Alberti *et al.* 2003, 1173 and Chew 2009, 148).

cultural, political, or economical—that are on a different disciplinary level from what are thought of as ecological variables, like foraging or dispersal strategies. Without including anthropogenic factors, the dynamics of “human-disturbed” systems appear unpredictable. To predict the changing composition of species making up a human-planted forest or city park an ecologist must include variables which capture the intentions of forest managers or urban designers.⁶

Acknowledging the now pervasive influence of humans on the planet, many recent ecologists have begun to include human activity in their models. They want an ecology that applies to human-disturbed as well as undisturbed landscapes, but this forces them to take into account economic processes. One field where this interdisciplinary exchange is occurring is biogeography (Thomas 2013; Mendenhall *et al.* 2013). The theory of island biogeography is particularly important because it has long been the foundation for estimating extinction rates, predicting changes in biodiversity, and making policy recommendations (Diamond 1975; He and Hubbell 2011). We present one recent example from this literature (Helmus *et al.* 2014).

The theory of island biogeography explains and predicts the species richness (that is, number of species) that will be found on an island at equilibrium (that is, when rates of species immigration to the island and species extinction on the island balance out) (MacArthur and Wilson 1967; Diamond 1975). In a recent paper, Helmus *et al.* (2014) tested the predictions of this theory for the distribution of *Anolis* lizard species among Caribbean islands. The theory predicts a strong negative relationship will be found between species richness and geographic isolation: as a result of decreased inter-island immigration, more isolated islands will contain fewer species than less isolated ones. It turns out that this prediction is false for Caribbean *Anolis* lizards because geographic isolation no longer determines immigration of new species. Rather, it is *economic* isolation that does so: islands that receive more cargo shipments are more likely to contain migrants from other islands, as lizards can move from island to island as stowaways on human cargo ships. For Caribbean lizards, that is, geographic isolation is of less influence on biodiversity than economic isolation. Estimating economic isolation from global maritime shipping-traffic data, Helmus *et al.* found that when economic isolation was substituted for geographic isolation, the new biogeographic theory fit with their data: anole richness was a negative function of economic isolation. They conclude that “Unlike the island

⁶ See Johnson and Swan (2014) for a discussion of human landscaping preferences that might help build predictive urban ecology models.

biogeography of the past that was determined by geographic area and isolation, in the Anthropocene [...] island biogeography is dominated by the economic isolation of human populations. [And] Just as for models of other Earth systems, biogeographic models must now include anthropogenic [variables] to understand, predict and mitigate the consequences of the new island biogeography of the Anthropocene” (Helmus et al. 2014, 543, 546). This is a clear case of unidirectional interdisciplinary exchange: in Grüne-Yanoff and Mäki’s terminology, non-disruptive interdisciplinary model-variable transfer by importation. The *exchange gain* in this case is predictive accuracy.

But the case is even stronger. Building anthropogenic factors into their biogeographic model also gives Helmus et al. a way to predict—with the aim of mitigating—the effects of decreasing economic isolation. For example, as economic isolation decreases, we must increase our efforts to protect exotic species from the immigration of non-native species, if that is the conservation strategy adopted. Traditional theories of biogeography that do not include anthropogenic factors may provide few resources—or worse, may actually suggest inapplicable, harmful strategies—for the conservation of these Caribbean lizards because the variables that make a difference are not included in the model. To know whether economic isolation is going to increase or decrease one must follow economic trends. For example, the US embargo increases Cuban economic isolation, and a cessation of the embargo would decrease isolation and increase species richness. Helmus *et al.* predict that Cuba would rapidly gain between 1 and 2 non-native anole species, a prediction that could not be made with the traditional (non-anthropogenic) biogeographic theory.

What can we learn from this example? Not that ecologists should always take anthropogenic factors into account in *every* case. Rather, that (i) there are cases in which not taking anthropogenic factors into account can be epistemically disadvantageous, such as diminishing our ability to predict the dynamics of certain systems, and (ii) that such cases are not limited to urban or agricultural settings, but range over cases of “pure” ecology such as the distributions of *Anolis* lizards on Caribbean islands.

Helmus *et al.*’s paper demonstrates that if the goal is the successful prediction of ecological systems, with the hope of providing helpful advice for policy interventions, there are compelling reasons for encouraging interdisciplinary exchange between ecology and economics. This is a clear case of when ecology needs economics: not taking anthropogenic

activities into consideration in the construction of a biological model diminishes our ability to predict the dynamics of systems to which that model *is* intended to apply.

Furthermore, connecting this discussion to that in Section 2, it is likely that as coupled human-natural systems, like anole distribution in the Caribbean, become the new norm, coupled economic-ecological models will be required. A science of ecology that leaves out anthropogenic factors will likely lose global relevance as the places in which its theories apply diminish. In other words, such an omission, whether based on a Galilean or minimal idealization, would be unwarranted. Rather than look at this with disappointment or scorn, a better response is to aim for models which *can* accommodate such systems, and this means championing interdisciplinary exchange.

Exchange gain is purchased at little cost in this case. It doesn't require the development of a new theoretical framework nor extensive disciplinary integration, and requires minimal bidirectional collaboration. Instead, what was needed was the substitution of a variable strongly influenced by economic trends—economic isolation—with one that is common in traditional ecology—geographical isolation. Here, traditional ecological theory is retained in a modified form. We call this type of interdisciplinary exchange *non-disruptive model-variable transfer*: an economic variable is simply substituted for an ecological one in a traditional ecological model. This might be contrasted with cases in which the development of new theory is required—cases of *disruptive model-variable transfer*.

5. When Economics Needs Ecology: Cutthroat Trout in Yellowstone Park

Economists have generally discounted the significance of ecological factors in their models and theories. They have often presumed that non-human factors are either fixed, exogenous, or disturbing causes. Even the most esteemed nineteenth century economic theorists who endorsed the Malthusian population principle downplayed the role of such factors in their models. David Ricardo, for instance, inaugurated this trend with his “corn model”, where land is depicted as an original and “indestructible factor of production” ([1817] 1951, 67.⁷ Subsequent Ricardians, such as John Stuart Mill ([1848] 2006), not only sanctioned this view of land but drove a wedge between the social and natural realms by repositioning the entire core of phenomena studied by economists such that human agency is the proximate cause (Schabas 2005).

⁷ See Morgan (2012, 44-81).

Today, many economists have begun to wrestle with their Ricardian inheritance. The Cambridge economist, Partha Dasgupta, for example, contends that resource economists can no longer afford to assume that “Nature” is an “indestructible factor of production” (2010, 6). Others have abandoned their Ricardian legacy altogether. In fact, the entire transdisciplinary field of research ecological economics emphasizes the significance of including social and ecological factors in coupled or ecological-economic models (Costanza 1989; Christensen 1989; Røpke 2005; van den Bergh 2001; Martinez-Alier and Røpke 2008). Be that as it may, ecological-economic modelling is not yet a widespread practice among mainstream resource economists (Wätzold *et al.* 2006).

According to Dasgupta, the central reason why resource economists should no longer assume that ecological factors are fixed is because this assumption can have harmful consequences if the goal is to make optimal policy prescriptions (Dasgupta *et al.* 2000). Simon Levin *et al.* (2013) and Kenneth Arrow *et al.* (1995) concur.

Levin *et al.* (2013) give the example of modelling coral reefs with conventional economic instruments, such as taxation, trading schemes, and quotas, and argue that without modelling such phenomena as complex adaptive systems (systems linking anthropogenic and non-anthropogenic factors), policy interventions are much less effective than they would be otherwise. Since the management of coral reefs is characterized by nonlinear feedbacks, strategic interactions, individual and spatial heterogeneity, and varying time scales, ignoring such complex characteristics lead to failures in predicting profound changes to economically important ecosystems. For instance, a coral reef may “flip” from having a healthy population of tropical fish to being an algae-dominated one and, by using a model that excludes the variables that determine such abrupt regime shifts, economists are incapable of predicting large negative economic consequences (in this case, for fisheries and tourism) associated with this kind of shift. Arrow *et al.* (1995) gives the example of including dynamic ecological factors in economic growth models. They argue that ecological factors, such as the carrying capacity of the environment, should be included in growth models to ensure that “the ecological systems on which our economies depend are resilient” (1995, 521). Their central worry is that modelling growth without accounting for the resilience of ecosystems could make societies unnecessarily sensitive to harmful external shocks. Growth models should be structured so that they never prescribe policies that undermine the ecological conditions that make human economic activity possible in the first place.

Nowhere are the epistemological and policy benefits of including ecological factors in economic models more evident than in the case of managing invasive species in Yellowstone National Park, Wyoming. When Yellowstone Lake was invaded by an exotic lake trout (*Salvelinus namaycush*), managers were worried that the growth of this species would significantly reduce the population level of the Yellowstone cutthroat trout (*Oncorhynchus clarki bouvieri*), a native species that supports an inland fishery and a variety of non-human species, such as ospreys, pelicans, river otters, and grizzly bears. Chad Settle *et al.* (2002) specified a model for two separate systems: the economic system in Yellowstone National Park and the ecosystem in and around Yellowstone Lake. They asked whether their model, which combines details of an economic system and an ecosystem with explicit feedback links (economic and ecological factors are jointly determined) between them, yields significantly different results than a model that ignores those links. Their economic-ecological model, predicted that when ecosystems change, people will change their economic behavior, which in turn affects the ecosystem; correspondingly, any alterations in the ecosystem affects human economic behavior, including economic production possibilities.

Settle *et al.* (2002) ran three different scenarios with their model. The best-case scenario is a hypothetical one, when the lake trout are costlessly eliminated from Yellowstone Lake. Under this optimistic scenario, the cutthroat trout would return to the lake as if the lake trout had never invaded in the first place. The worse-case scenario occurs if the lake trout are left to their own devices, which would have the effect of producing the smallest viable population of cutthroat trout. Their third policy scenario involved the National Park Service gillnetting the lake trout in order to reduce the risk to cutthroat trout populations.

Their results showed that a dynamic model that integrates ecological and economic systems *with feedback links between the two systems* yields significantly different results than when one that ignores these links. In every scenario they outline, cutthroat trout populations differ in both magnitude and survival rates once feedback is allowed between the two systems. For both the best-case and policy scenarios, Settle *et al.* (2002) predicted the steady state population of cutthroat is lower without feedback than with feedback. Given the worst-case scenario, however, ignoring feedback leads to estimating a relatively high cutthroat population. Settle *et al.* concluded that “basing policy recommendations in Yellowstone Lake on data from models without feedback puts cutthroats at greater risk than would be true if feedback was explicitly considered” (2002, 309). In this case, the policy recommendations

derived from a model without ecological factors would be worse than those derived from a model that connects the economic system to an ecological system with explicit feedback links.

As with the Helmus *et al.* case in the previous section, the exchange gain in the cutthroat trout example can be purchased rather cheaply. The latter does not require the development of a completely new theory or bidirectional collaboration. Instead, Settle *et al.*'s model merely required the addition of feedback variables that link two jointly determined systems. In this case, the economic variables that constitute the economic system, are not jettisoned or even supplanted by another variable. Rather, the traditional economic theory is retained, but in a supplementary form. Again, in accordance with Grüne-Yanoff and Mäki's taxonomy, we can call this type of interdisciplinary exchange *non-disruptive model-system transfer by interfield importation*: an ecological system with feedback links is connected to a traditional economic system. This exchange contrasts sharply with types of disruptive model transfer involving the development of entirely new theory.

6. Conclusion

Recent scientific evidence forces scientists to acknowledge the prevalence of systems containing factors that transgress disciplinary boundaries. This state of affairs has consequences for both ecology and economics. The practitioners of these two sciences have traditionally found themselves occupied with phenomena on opposite sides of the human-natural divide. Yet, in many cases, human-natural coupled systems are the new norm. We have argued that there are specific cases in which these sciences fare better, epistemologically and in terms of policy prescriptions, when they work together to build models that contain anthropogenic and non-anthropogenic factors, compared to when they address these factors separately. In the first case, ecologists demonstrated that substituting an ecological variable for an economic one gave rise to a model which had a better fit with current data and offered better prospects for predicting future changes in biodiversity. In the second case, economists maintain an economic system from their model, but connect it to a distinct system, an ecological system, with feedback variables that link the two systems together. Of course, our claim is not that ecology always needs economics, and economics always needs ecology. Modelling organism behavior in the trenches of the deep ocean, for example, may not require economics and predicting the unemployment rate will almost certainly not benefit from ecology.

Our analysis contributes to the recent literature about interdisciplinarity in three ways. First, we explored what makes interdisciplinarity indispensable in some cases and argued that recent scientific evidence demonstrating that human-natural coupled systems are the new norm should itself encourage interdisciplinary exchange, and we spelled this out in terms of exchange gain in two different case studies. Second, we showed that exchange between disciplines can bring about epistemological advantages without requiring disciplinary integration. This conclusion is striking because many philosophers of science have supposed that the integration in this sense is essential to interdisciplinary science (Brigandt 2013). By contrast, our paper provides further evidence to support the relatively new claim that successful interdisciplinary interaction does not always require integration (Grüne-Yanoff 2016). And finally, we provided two new types of interdisciplinary exchange to add to Grüne-Yanoff and Mäki's (2014) taxonomy.

Our analysis also has a wider implication: although disciplinary boundaries are sometimes not scientifically-informed, interdisciplinary interactions should be. As with many sciences, disciplinary ideals (and idealizations) tend to discourage cross-disciplinary interaction. As in the quotation by ecologist James Brown above, interactions between ecologists and economists have been structured by ideas of purity: “pure” ecologists study non-human nature and “pure” economists often overlook non-human nature (Brown 1995). Yet, we have strong scientific evidence to believe that most of the terrestrial globe consists of coupled human-natural systems, and we have just provided evidence that such systems are better considered as wholes, rather than the separate objects of two independent sciences. Our aim has not been to argue that we should revolutionize the divisions of science, but to urge that they do not always reflect evidence about our current world, and thus that the divisions themselves should not structure or determine interactions across disciplines. We agree with ecologists Boris Worm and Robert Paine that “the recognition of a novel geological epoch might also provide a new focus for ecology and the study of humans as a primary and dominant component of contemporary ecosystems,” but we’d add that this will require interaction with social scientists, including economists (Worm and Paine 2016, 601). And, the reverse is true as well: it is to be expected that, in a growing number of cases, economics will need ecology, too. Indeed, in the age of the Anthropocene, without interdisciplinary exchange it is to be expected that ecology and economics would relinquish global relevance because the distinct and separate systems to which each pure science applies will only diminish over time.

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